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Transient Response to Rapid Cooling of a Stainless Steel Sodium Heat Pipe

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Abstract. Compact fission power systems are under consideration for use in long duration space exploration missions. Power demands on the order of 500 W_e to 5 kW_e will be required for up to 15 years of continuous service. One such small reactor design consists of a fast spectrum reactor cooled with an array of in-core alkali metal heat pipes coupled to thermoelectric or Stirling power conversion systems. Heat pipes advantageous attributes include a simplistic design, lack of moving parts, and well understood behavior. Concerns over reactor transients induced by heat pipe instability as a function of extreme thermal transients require experimental investigations. One particular concern is rapid cooling of the heat pipe condenser that would propagate to cool the evaporator. Rapid cooling of the reactor core beyond acceptable design limits could possibly induce unintended reactor control issues. This paper discusses a series of experimental demonstrations where a heat pipe operating at near prototypic conditions experienced rapid cooling of the condenser. The condenser section of a stainless steel sodium heat pipe was enclosed within a heat exchanger. The heat pipe – heat exchanger assembly was housed within a vacuum chamber held at a pressure of 50 Torr of helium. The heat pipe was brought to steady state operating conditions using graphite resistance heaters then cooled by a high flow of gaseous nitrogen through the heat exchanger. Subsequent thermal transient behavior was characterized by performing an energy balance using temperature, pressure and flow rate data obtained throughout the tests. Results indicate the degree of temperature change that results from a rapid cooling scenario will not significantly influence thermal stability of an operating heat pipe, even under extreme condenser cooling conditions.

Keywords: Heat pipe, space, nuclear, transient, cooling, compact, reactor.

BACKGROUND

Deep space mission power demands have been traditionally supplied through the use of radioisotope thermoelectric generators (RTGs). However, the severe shortage of Pu-238 will likely limit mission power requirements to a few hundred Watt-electric (W_e) even if production of the isotope where to begin immediately. In order to diversify the space power options, compact fission reactors are under consideration for power generation required for long duration deep space missions. Power demands on the order of 500 W_e to 5 kW_e are required with safe and reliable operation for up to 15 years of continuous service[1]. Advanced reactor fuels developed by the Department of Energy (DOE) as well as reactor core cooling, energy conversion, and heat rejection technologies developed by NASA provide the necessary technologies currently available to successfully develop compact reactor systems. These compact reactors designs have relatively low mass, low complexity, low cost, are reliable and can be available for service within a few years. No major technological breakthroughs are required to increase the technology readiness level of compact reactors to flight status. A step-wise technology development program emphasizing component, sub-system, and system hardware demonstration is under review.

Compact Reactor Design Concept

One compact reactor design envisioned by a joint NASA-DOE team consists of a Uranium-10%Molybdenum fueled fast spectrum reactor, cooled with 18 in-core alkali metal heat pipes coupled to either thermoelectric or Stirling power conversion systems[1]. Heat pipes present a number of advantages based on a simplistic design, lack of moving parts, and well understood behavior[2,3]. Heat pipes have not been used as reactor primary cooling (although there is significant experience with reactor thermal simulators) and some perceived uncertainty exists regarding potential off-nominal operating conditions. This perceived uncertainty has been the basis for preventing application of heat pipes as the primary reactor coolant system and not due to lack of demonstrated performance data.

PROBLEM STATEMENT AND OBJECTIVES

Concerns over reactor transients induced by heat pipe instability as a function of thermal transients have been raised and require experimental investigation. One perceived concern is the rapid cooling of the heat pipe condenser section that may subsequently cool the evaporator section beyond acceptable design limits. Since the reactor design utilizes a negative temperature reactivity feedback coefficient, rapidly decreasing the reactor core temperature could result in an unintended positive reactivity insertion. This paper details a series of experimental demonstrations conducted at the NASA Marshall Space Flight Center (MSFC) where a heat pipe operating at near prototypic conditions experienced rapid cooling of the condenser. The resulting thermal transient behavior of the heat pipe was observed in order to evaluate the effect of thermal stability of in-core heat pipes induced by extreme condenser cooling.

APPARATUS AND PROCEDURE

Three graphite resistance heaters in tubes radially surrounding the evaporator of a stainless steel/sodium heat pipe provide the appropriate simulated nuclear fuel element thermal environment. The heat pipe evaporator was well insulated with multiple layers of stainless steel foil, fibrous alumina blankets and aluminum foil. A concentric two-pass gas heat exchanger was designed, fabricated, tested, and installed over the condenser end of the heat pipe. The appropriate amount of gaseous nitrogen (GN2) flowed through the heat exchanger via a mass flow controller coupled to the LabView based data acquisition and control program. An array of type-K thermocouples were used to measure the temperature distribution throughout the heat pipe, heat exchanger, and resistance heater assembly as illustrated in Figure 1.

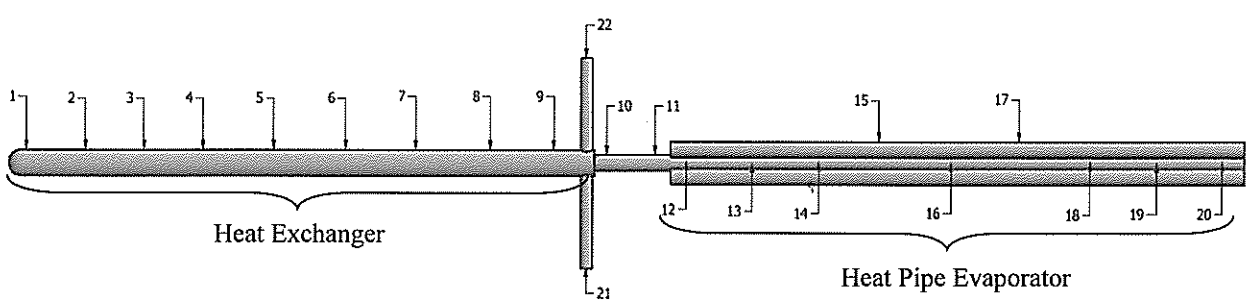

FIGURE 1. Thermocouple locations

The heat exchanger inlet pressure and flow rate were measured by a mass flow controller and the outlet pressure was measured with an absolute pressure transducer. The inlet and outlet nitrogen stream centerline temperatures were measured directly with thermocouples. The heat pipe – heat exchanger assembly was placed in a vacuum chamber as illustrated in Figure 2.

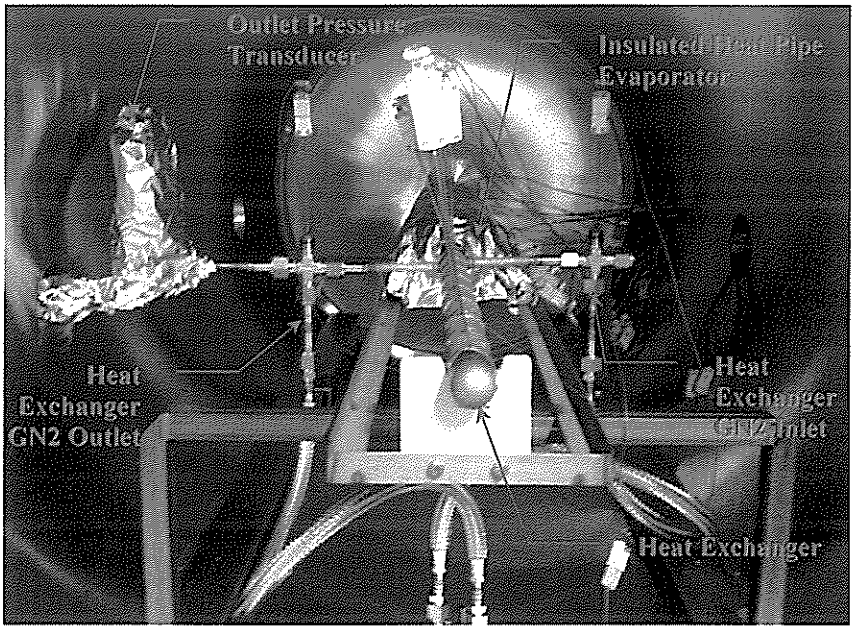

FIGURE 2. The heat pipe/heat exchanger assembly in the vacuum chamber with instrumentation and insulation.

Resistance heater control, GN2 flow control, instrumentation measurement and data recording were achieved through the use of a LabView data acquisition and control program. The vacuum chamber with the associated instrumentation, data acquisition panel, support equipment, power supply, and control rack is illustrated in Figure 3.

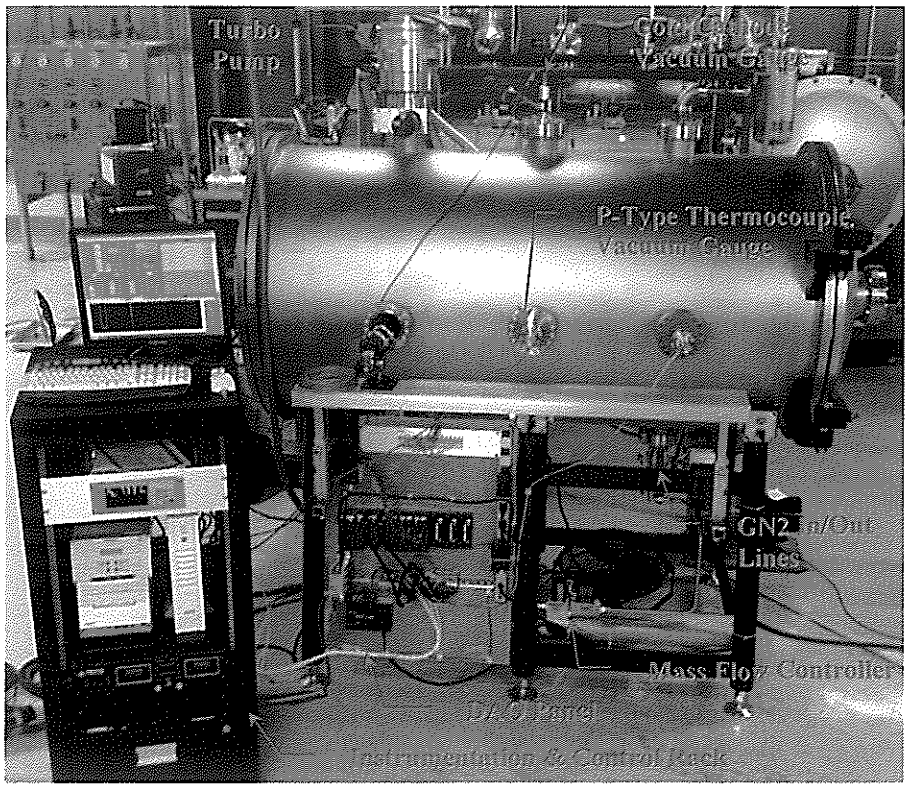

FIGURE 3. Vacuum chamber, DAQ panel, instrumentation & control rack

The vacuum chamber was evacuated to a pressure of $1x10^{-3}$ Torr, at which point the assembly was heated to 110 ± 3 °C using the resistance heaters in order to volatilize impurities and absorbed water. As expected the pressure increased with volitization then decreased under continued evacuation. The heaters were shut off and the assembly was cooled to ambient temperature where a steady pressure of 5.4×10^{-6} Torr was established. Finally, the chamber was back filled with 50 Torr of ultra-high purity helium for improved thermal coupling of the resistance heaters to the heat pipe in preparation for testing. Heat pipe start-up procedure was conducted over a two hour period, with onset of start-up indications observed at between 400 and 450 °C. The heat pipe was brought to a nominal steady state evaporator temperature condition of between 510 to 530 ± 5 °C. Temperature was controlled with input power, which varied from 450 to 825 ± 1 W_e. Heat input was estimated using the measured current and voltage applied to each heater connected in parallel. Once a steady state operating condition was reached the mass flow controller established a flow of 500 ± 1 standard liters per minute (SLPM) of cold GN2 through the heat exchanger. During cooling the power supply maintained a constant heater input power. Once the heat pipe reached a new stable operating condition the gas flow was terminated and the heat pipe recovered to the prior stable operating conditions that existed before cooling of the condenser. Heat removal was estimated by performing a thermal energy balance on the both the heat exchanger and the vacuum chamber using measured values for temperature, pressure, and flow rate.

RESULTS

Practice trials were conducted to establish an iteratively based standardized test protocol. An example of a test profile from start-up, through cooling transient, and post-cooling recovery is illustrated in Figure 4.

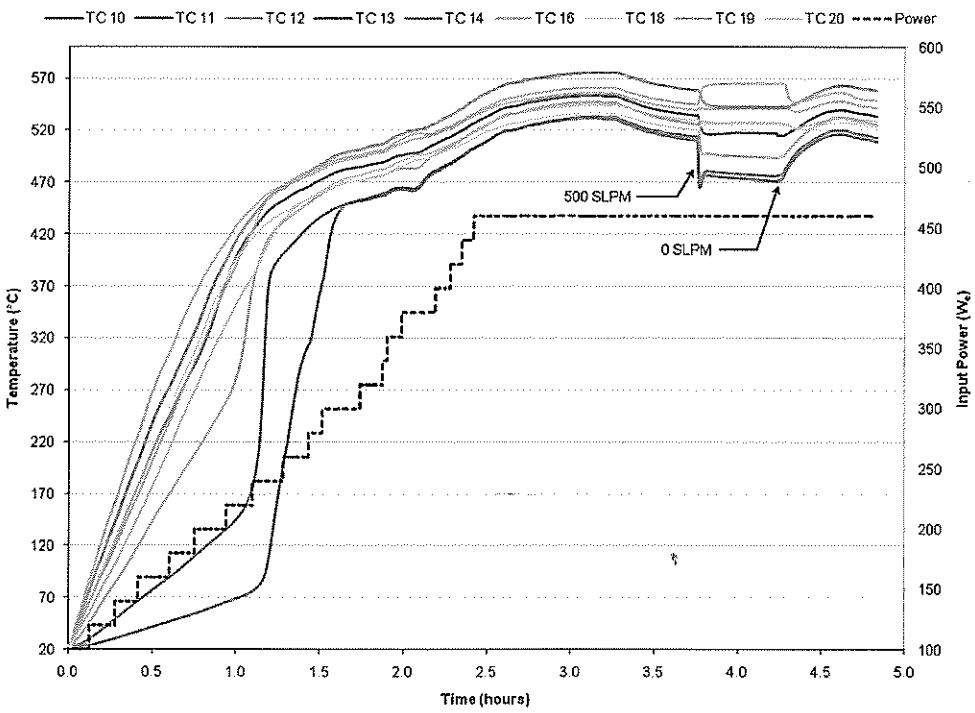

FIGURE 4. Heat pipe start-up, steady state operation at 460 W_e input, condenser cooling transient, and recovery.

An input power of 460 W yielded a steady state evaporator temperature of between 510 to 530 ± 5 °C. After reaching stable conditions, flowing 500 SLPM of GN2 through the heat exchanger resulted in rapid cooling of the heat exchanger to near room temperature within a 30 minute period as shown in Figure 5.

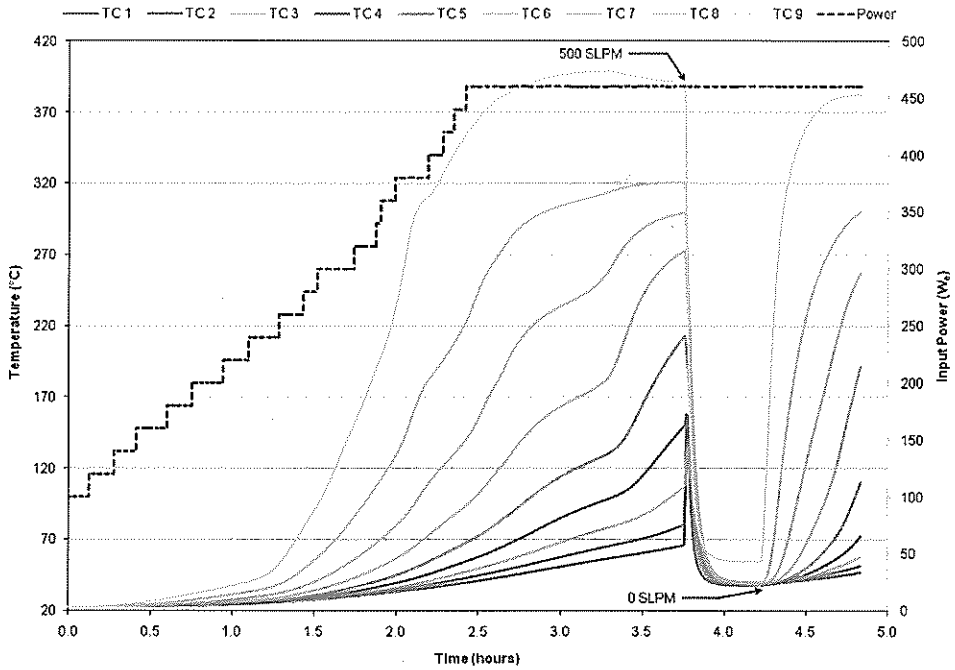

FIGURE 5. Heat exchanger temperature transient with 460 W_e input

As expected the temperatures fan out during heating and converge during active cooling. TC9 does not completely converge with the other measurements and is due to placement directly on the coupling to the heat pipe and thus is experiencing more heat conduction at its location. As expected the evaporator temperature distribution did not experience the same degree of temperature change compared to the heat exchanger. The evaporator underwent a small decrease in overall temperature distribution of between 472 to 526 ± 5 °C as illustrated in Figure 6.

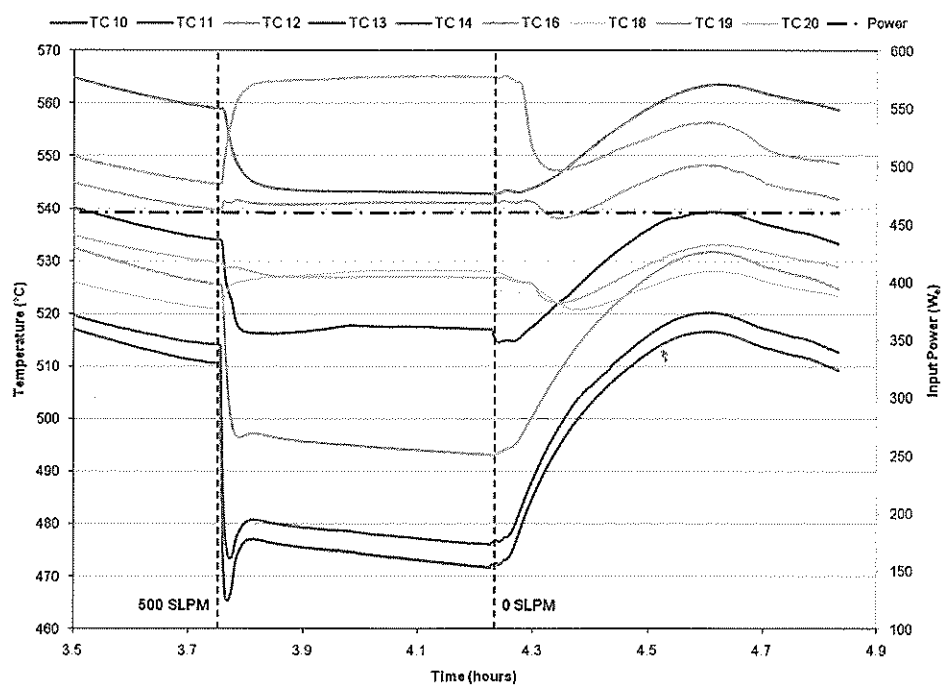

FIGURE 6. Heat pipe evaporator temperature transient with 460 W_e input

TC10 and TC11 are the most reliable heat pipe measurements because they are at the evaporator exit, mounted directly on the heat pipe with the best TC to surface contact. These two TCs show a heat pipe evaporator exit temperature of between 470 and 480 °C. Ensuring uniform contact of the TCs to the heat pipe surface during temperature changes is difficult. Measurement error associated with variation in contact of the TCs to the heat pipe is fairly substantial and exceeds the inherent uncertainty and measurement error of the type K TCs. This contact uncertainty can be attributed with much of the variation in the temperature distribution since once started a heat pipe should have a uniform temperature along its surface. The heat pipe continued to operate with little change in performance throughout the cooling transient. During the cooling process the heat pipe displayed no indications of stall or shutdown; however, TC19 did experience an increase in temperature. Possible explanation for this departure from expected nominal performance is under investigation but could be variation in TC contact to the surface or possibly the onset of dry out. Once steady cooling conditions were achieved, GN2 flow was terminated and the heat pipe recovered to the nominal temperature distribution within a period of less than 30 minutes. During the recovery period temperature fluctuations vary initially upon reaching the new stable operating condition but these oscillations quickly dampen.

An energy balance analysis was performed on the heat exchanger and the vacuum chamber in order to understand the overall performance of the system. The heat removal from the test assembly by the actively cooled gas flow heat exchanger and thermal losses (conductive and radiative) from the vacuum chamber to the environment as illustrated below in Figure 7.

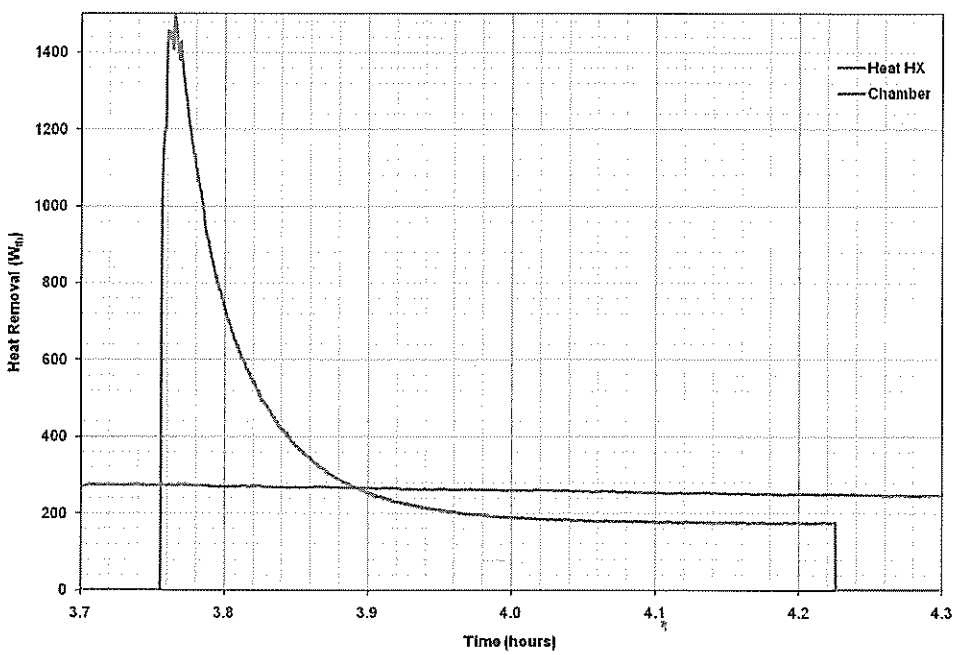

FIGURE 7. Energy balance of heat removal from the heat exchanger and vacuum chamber (460 W_e input)

Measured results agree with predicted performance determined during the design phase. The spike in heat removal can be attributed to the energy stored in the heat exchanger material, which is significant when compared to the heat pipe material mass. Once the heat exchanger thermal inertia is overcome by the cooling gas, the approximate energy removal by both the heat exchanger working fluid and parasitic loss (heat pipe – heat exchanger assembly to the chamber to the environment) can be seen at the new steady state operating point. Less than 10% of energy loss is not accounted for and is likely due to resistive losses in power and instrumentation lines and associated measurement error.

Next, cooling tests are repeated starting at a higher steady state operating temperature. These higher temperature tests were accomplished by increasing the input heater power from 460W_e to 825 W_e. The increased power input resulted in an evaporator temperature distribution that varied between 660 to 720 ± 6 °C during steady state operation. Flowing 500 SLPM of GN2 through heat exchanger again resulted in rapid cooling with the heat exchanger average surface temperature, asymptotically approaching approximately 65 °C within a period of less than 30 minutes. The evaporator temperature distribution before the introduction of GN2 in to the heat exchanger varied from 676 to 726 °C. After the onset of rapid cooling the evaporator temperature distribution did show an overall decrease from between 545 to 739 °C. However, the heat pipe took approximately 60 minutes to reach a new steady state condition, indicating a significantly larger thermal time constant when compared to the long approach to steady state for the heat exchanger. The 825 W_e input power transient behavior test results are illustrated in Figure 8.

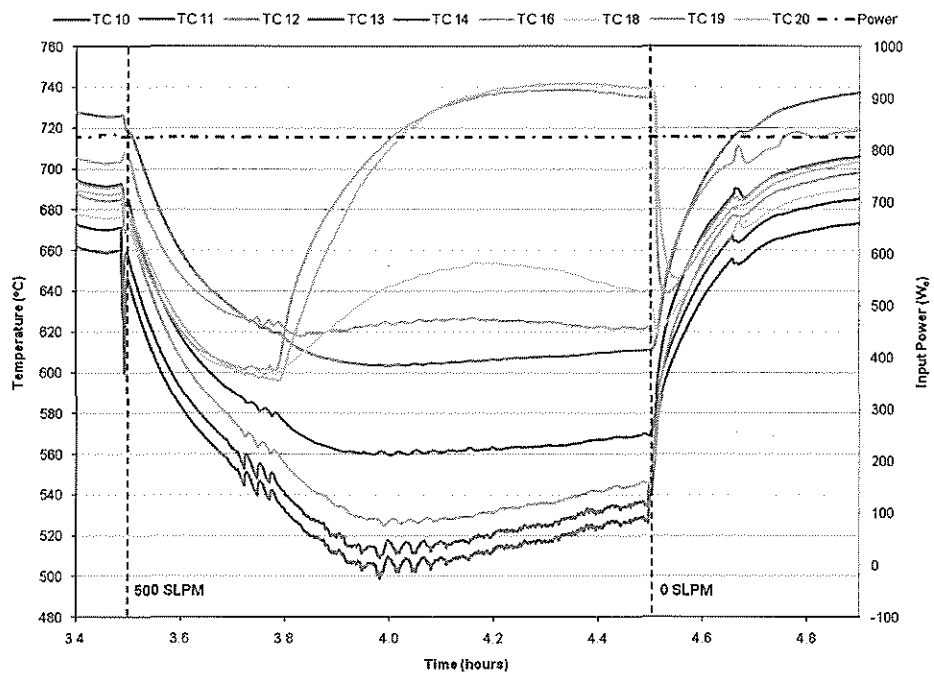

FIGURE 8. Heat pipe evaporator temperature transient with 825 W_e input

The resulting change in temperature distribution is similar to that of the lower temperature tests. The aft-most thermocouples (TCs 18, 19 20) show a significant increase in temperature. The magnitude of the shift is outside the range of instrumentation error. The reason for this temperature shift is unknown and is currently under investigation. Departure from nominal operation could be approach to heat pipe dry out or possibly stagnation block. Changes in TC surface contact is an unlikely explanation since the performance returns to normal after post-cooling recovery. Eventually, stable operating conditions were achieved during the maximum cooling phase. After the GN2 coolant flow was terminated the heat pipe quickly returned to steady operating conditions experienced before the cooling transient occurred.

A comparison of the temperature distribution pre, during, and post cooling for the 460 W and 825 W tests are illustrated in Figures 9 and 10. For lower power tests we do observe some temperature peak shifting to the rear of the heat pipe, which would be expected as heat is conducted away from the evaporator. For higher power tests the temperature profile remains relatively the same only at a lower average surface temperature and some peak temperature shifting is observed. These transient responses to rapid cooling show no evidence of mass flux entrainment, stall, or shut down. It can be inferred that although the average heat pipe surface temperature decreases, the overall performance is not significantly affected by

rapid cooling of the condenser section. Such large time constants observed from these transient tests can easily be compensated for by the reactor core if such an unlikely event was to actually take place.

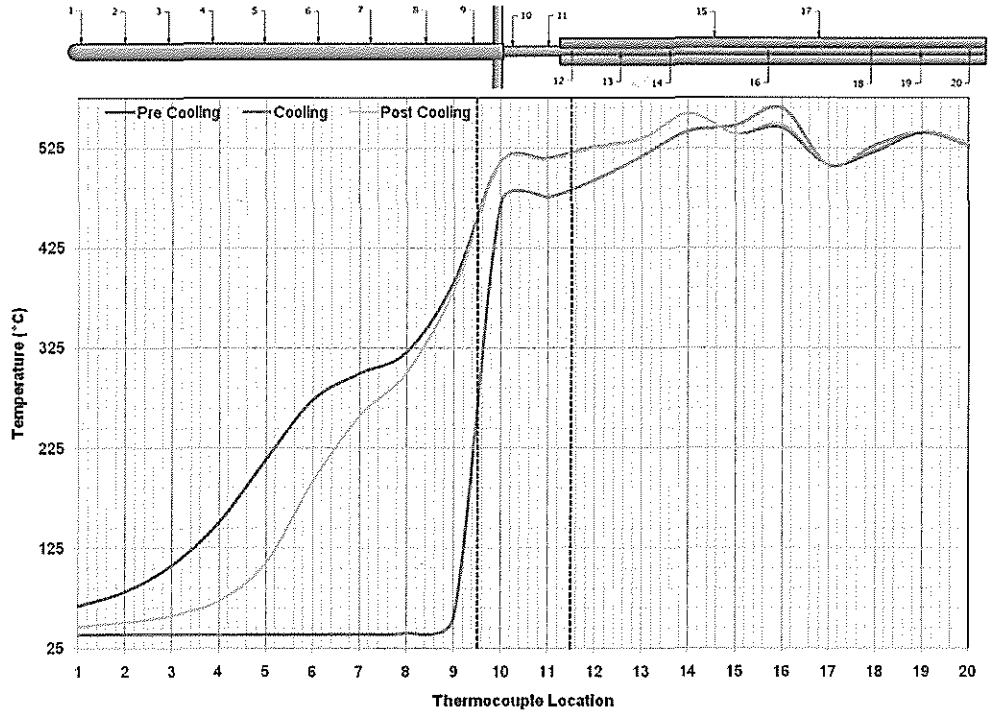

FIGURE 9. Temperature distribution comparison before and after cooling (460 W_e input)

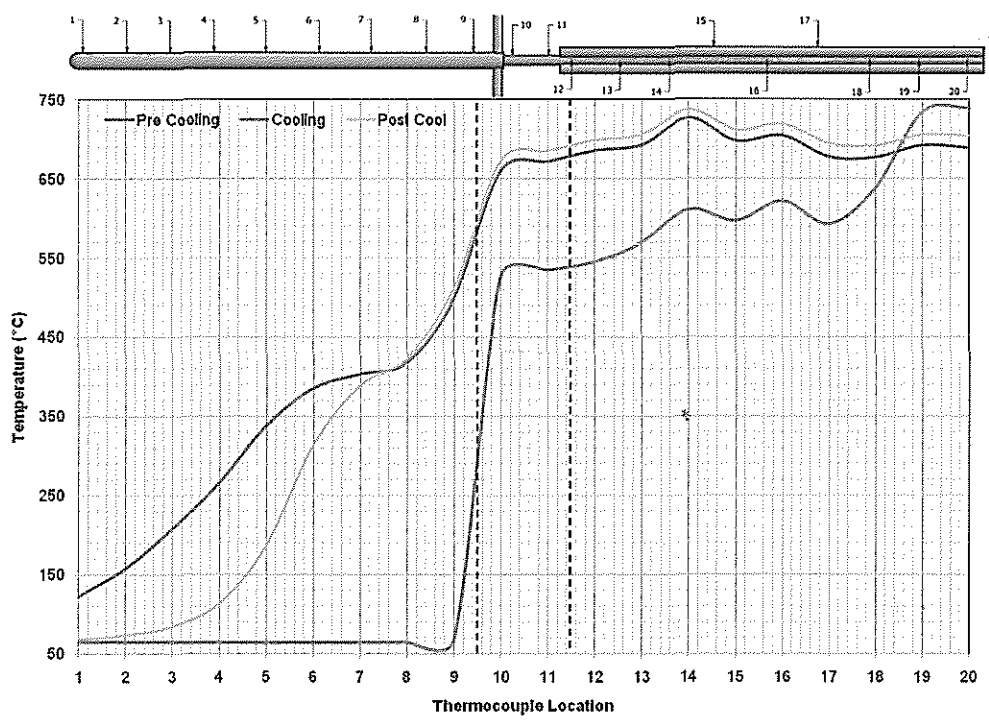

FIGURE 10. Temperature distribution comparison before and after cooling (825 W_e input)

CONCLUSION

Results from the series of experimental demonstrations indicate the degree of temperature change that results from an unlikely rapid cooling scenario does not occur at a fast enough time scale to significantly affect the overall performance of the heat pipe. The rate of temperature change is easily within the reactor's passive reactivity feedback ability to compensate for changes in heat pipe output. No manifestation of mass flux entrainment, heat pipe stall, or heat pipe shut down was evident. The departure from nominal operation of the aft most thermocouple measurements may be evidence of onset of heat pipe performance change via approach to dry out. In summary, the heat pipe maintained thermal stability and demonstrated reliable reactor core cooling performance even under extreme condenser cooling scenarios.

NOMENCLATURE

GN2 = Gaseous nitrogen
Pu = Plutonium
T = temperature (°C)
TC = Thermocouple
SLPM = Standard Liter Per Minute
W_e= Watt-electric

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